

The GAIA astrometric survey of extra-solar planets

M. G. Lattanzi¹, S. Casertano², A. Sozzetti^{3,1} and A. Spagna¹

¹ *Osservatorio Astronomico di Torino, 10025 Pino Torinese, Italy*

² *Space Telescope Science Institute, Baltimore, MD 21218, USA*

³ *University of Pittsburgh, Dept. of Physics & Astronomy, Pittsburgh, PA 15260, USA*

Abstract

The ESA Cornerstone Mission GAIA, to be launched prior to 2012 and with a nominal lifetime of 5 years, will improve the accuracy of Hipparcos astrometry by more than two orders of magnitude.

GAIA high-precision global astrometric measurements will provide deep insights on the science of extra-solar planets. The GAIA contribution is primarily understood in terms of the number and spectral type of targets available for investigation, and characteristics of the planets to be searched for. Several hundreds of thousands of solar-type stars (F-G-K) within a sphere of ~ 200 pc centered on our Sun will be observed. GAIA will be particularly sensitive to giant planets ($M_p \sim M_J$) on wide orbits, up to periods twice as large as the mission duration, the potential signposts of the existence of rocky planets in the Habitable Zone. Thousands of new planets might be discovered, and a significant fraction of those which will be detected will have orbital parameters measured to better than 30% accuracy. By measuring to a few degrees the relative inclinations of planets in multiple systems with favorable configurations, GAIA will also make measurements of unique value towards a better understanding of the formation and evolution processes of planetary systems.

1 INTRODUCTION

The present catalogue of candidate extra-solar planets discovered by radial velocity surveys (see for example [1]) totals today 66 objects having minimum mass $M \sin i \leq 13 M_J$ (where M_J is the mass of Jupiter), the so-called deuterium-burning threshold. Orbital periods span a range between a few days and ~ 7 years, but $\sim 80\%$ of these objects revolves around the parent star on orbits with semi-major axis $a < 1$ AU, well outside the ice condensation zone. Orbital eccentricities are usually higher than in our Solar System, up to ~ 0.9 for HD 80606 [2]. Seven stars harbor multiple systems, formed by either two or three planets [3–6], or a planetary mass object and a probable brown dwarf [7–9].

Except for the case of HD 209458 [10], all low-mass companions to solar type stars having $M_p \leq 13 M_J$ have been classified as extra-solar planets solely on the basis of their small projected masses, and thus, under the reasonable assumption of randomly oriented orbital planes on the sky, small true masses. But, some of them may not be planets at all, as $\sim 1/5$ of them have $M \sin i > 5 M_J$. As a matter of fact, today the true nature of these objects is still matter of ongoing debates among the scientific community: for example, planet (and brown dwarf)

candidates, and stellar binaries have remarkably similar orbital elements distributions [11], but the mass functions in the two cases are strikingly different [12].

Clearly, our present understanding of the origin of planetary systems is still limited, and more measurements will be needed in order to be able to discriminate among models. To go beyond a simple **Catalogue** of extra-solar planets, **Classification** will have to be made on the basis of the knowledge of their true masses, shape and alignment of the orbits, structure and composition of the atmospheres. The dependence of planetary frequencies with age and metallicity will have to be understood. Finally, important issues on planetary systems evolution, such as coplanarity and long-term stability, will have to be addressed. But, the big picture will not be complete without crucial **New Discoveries**. The existence of giant planets orbiting on Jupiter-LIKE orbits (4-5 AU, or more) will have to be established. Such objects are the signposts for the discovery of rocky planets orbiting in regions closer to their parent stars, maybe even inside the star's Habitable Zone (for its definition, see Section 2.2). The proof of the existence of Earth-LIKE planets would be an extraordinary step towards the ultimate goal of the discovery of extra-terrestrial life.

2 THE ROLE OF GAIA

GAIA's ability in detecting and measuring planets is twofold, it will impact both future planet discoveries as well as provide information of great value for a complete classification of planetary systems and overall assessment of the correct theories of planet formation and evolution. In particular, the uniqueness of the GAIA contribution to the science of extra-solar planets is better understood in terms of 1) the size of the GAIA sample of potential systems which might be discovered and measured, 2) GAIA's ability in revealing the existence of a possibly large number of systems which might be bearing rocky, perhaps habitable planets, and 3) the impact of GAIA's coplanarity measurements in multiple-planet systems on the theoretical models of formation and evolution of planetary systems.

2.1 The size of the GAIA sample

In our earlier work [13], we considered in the simulations single giant planets, in the mass range $0.1 \leq M_J \leq 5$, orbiting $1-M_\odot$ stars with periods up to twice the mission duration, and placing the systems at increasing distances from our Sun. We parameterized our results in terms of the astrometric signal-to-noise ratio α/σ_ψ between the astrometric signature α and the single measurement error, which we set to $\sigma_\psi = 10 \mu\text{as}$ (implying a final accuracy of $4 \mu\text{as}$), value which applies to stars brighter than $V = 13$. In practice, this choice for the mass of the parent star encompasses the spectral class range from $\sim F0$ to early K type dwarf stars, whose masses are within a factor of ~ 1.5 that of the Sun. This, in combination with the $V < 13$ magnitude limit, translates into a distance cutoff for detection and accurate orbit estimation of ~ 200 pc. To this distance, F-G-K type dwarfs dominate the star counts at bright magnitudes, and within this horizon modern galaxy models [14] predict some $3 - 5 \times 10^5$ solar-type dwarfs available for investigation. Knowing the stellar content in the solar neighborhood and the planetary frequency distribution, we can extrapolate a number of potential planetary systems within GAIA's detection horizon. Early estimates [15] yield an integral planetary frequency of $\sim 3 - 4\%$ for giant planets in the mass range $0.5-5 M_J$ orbiting within 3 AU from the parent star. By assuming a uniform planetary frequency distribution with orbital semi-major axis [16], then we can derive a *lower limit* to the number of giant planets GAIA would detect and measure at a given distance d (in pc). In Table 1 we summarize the results. The values of N_d at different distances correspond to actual *new detections*, once the fractions of detected

Table 1. Number of giant planets that could be revealed by GAIA (N_d), and fraction of detected planets having accurate orbital elements determined (N_m), as a function of increasing distance from the Sun (Δd). A uniform frequency distribution of 1.3% planets per 1-AU bin is assumed

Δd (pc)	N_\star	Δa (AU)	N_d	N_m
0-100	$\sim 61\,000$	1.3 - 5.3	> 1600	> 640
100-150	$\sim 114\,000$	1.8 - 3.9	> 1600	> 750
150-200	$\sim 295\,000$	2.5 - 3.3	> 1500	> 750

giant planets in common with the overlapping semi-major axis regions at lower distances have been properly subtracted.

Therefore, the total number of giant planets GAIA could discover orbiting around normal stars within the distance limit of 200 pc from the Sun is then *greater* than 4700, and roughly 50% of the detected planets would have orbital parameters and masses good to 20 – 30%, or better. The statistical value of such a sample (comparable in size to that of the observing lists of the largest ground based surveys) would be instrumental for critical testing of theories on planet formation and evolution.

2.2 GAIA and the Habitable Zones

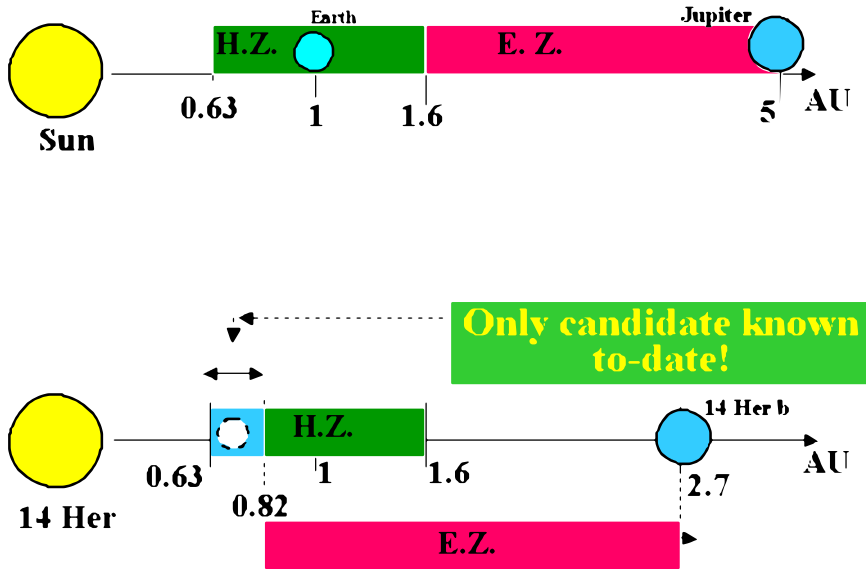


Fig. 1. Upper half: comparison between the Solar System’s Habitable Zone (in green) and Exclusion Zone (in red). Jupiter’s orbital period is sufficiently large that the entire Habitable Zone of the Sun is available for formation of rocky planets. Lower half: the same comparison in the case of the 14 Her system, the only one known to-date to bear a giant planet on a sufficiently large orbit for at least part of the Habitable Zone (in blue) to be able to host in principle a rocky planet

With the current payload design [19], the range of planetary masses between 1 Earth-mass and a few Earth-masses (Neptune-class planets) will only be marginally accessible to GAIA's all-sky survey. Its astrometric accuracy will be sufficient to address the issue of their existence only around a handful of the closest stars, within 5-10 pc from the Sun.

Nevertheless, GAIA's contribute to the search for rocky, possibly habitable planets will be significant. Theory, in fact, provides us with two important concepts: Habitable Zone and Exclusion Zone. The Habitable Zone [17] is defined by the distance from a given star at which the temperature is such that water can be present in the liquid phase. The center of the Habitable Zone (whose distance depends on the mass of the central star) can be roughly identified by the formula $P/P_{\oplus} = (M/M_{\odot})^{1.75}$. The Exclusion Zone [18] is defined by the dynamical constraint $P_G > 6 \times P_R$, which states that for a rocky planet to form in the Habitable Zone of a star then a giant planet must form on an orbital period P_G at least six times larger than the period P_R of the rocky planet. In Figure 1 we show these two concepts as they have been realized in our Solar System and in the only other interesting candidate known to-date, the 14 Her planet-star system. All those systems GAIA will discover harboring a giant planet on a sufficiently wide orbit ($a \geq 3$ AU) would immediately be added to the list of targets for the next generation of missions which will search the Habitable Zones of such systems for evidence of the existence of terrestrial planets.

2.3 GAIA and the planetary systems

The observational evidence of the first extra-solar planetary systems, whose unexpected orbital configurations are very unlike the Solar System's, has immediately raised crucial question regarding their formation and evolution. Are the orbits coplanar? Are the configurations dynamically stable? Radial velocity measurements cannot determine either the inclination i of the orbital plane with respect to the plane of the sky, or the position angle Ω of the line of nodes in the plane of the sky. General conclusions on the architecture, orbital evolution and long-term stability of the newly discovered planetary systems cannot be properly assessed without knowledge of the full set of orbital parameters and true mass values.

GAIA will be capable of detecting and measuring a variety of configurations of potential planetary systems. Utilizing as a template the two outer planets in the ν Andromedæ system, we have found [20] how a 60-pc limit on distance holds for detection and measurement accurate to 30%, or better, of *planetary systems* composed of planets with well-sampled periods ($P \leq 5$ yr), and with the smaller component producing $\alpha/\sigma_{\psi} \geq 2$. Also, accurate coplanarity tests, with relative inclinations measured to a few degrees, will be possible for systems producing $\alpha/\sigma_{\psi} \geq 10$ [20].

The frequency of multiple-planet systems, and their preferred orbital spacing and geometry are not currently known. Based on star counts in the vicinity of the Sun extrapolated from modern models of stellar population synthesis, constrained to bright magnitudes ($V < 13$ mag) and solar spectral types (earlier than K5), we should expect $\sim 13\,000$ stars to 60 pc [16]. GAIA, in its high-precision astrometric survey of the solar neighborhood, will observe each of them, searching for planetary systems composed of massive planets in a wide range of possible orbits, making accurate measurements of their orbital elements and masses, and establishing quasi-coplanarity (or non-coplanarity) for detected systems with favorable configurations.

3 HOW CAN GAIA ACHIEVE THIS?

Two major issues can be singled out at the moment of defining the crucial steps which must be undertaken in order for GAIA to fully accomplish the scientific goals in the field of extra-

solar planetary systems which have been outlined in the previous sections. First, specific requirements on the instrument performance must be met, and secondly it will be essential to identify the most robust and reliable procedures of analysis of the actual observational data.

3.1 The GAIA instrument

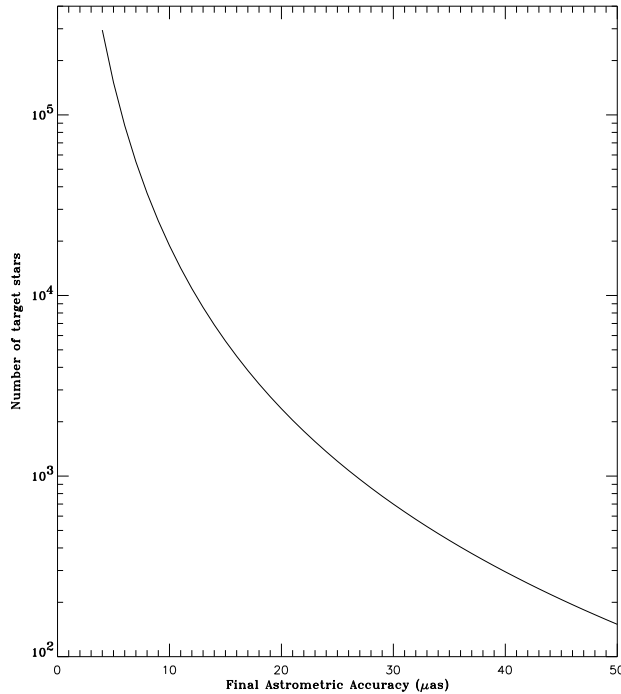


Fig. 2. Number of solar-type stars available for planet searches with GAIA, as function of the final accuracy on positions, proper motions, and parallaxes. If the final astrometric error is $8 \mu\text{as}$ instead of 4, then the size of the sample decreases by an order of magnitude ($\sim 2 \times 10^4$ vs. $\sim 3 \times 10^5$). In the limiting case of final astrometric accuracy equal to that of DIVA and FAME on bright objects, then the number reduces to some 150 stars)

In order to fulfill the expectations for ground-breaking results in field of planetary science, the GAIA instrument [19] must meet the stringent requirement of $4 \mu\text{as}$ final astrometric accuracy on positions, proper motions, and parallaxes for bright targets ($V < 13$). In fact, in order to keep the ratio $\alpha/\sigma_\psi = \text{const.}$, an increase in the measurement error implies an increase in the astrometric signature due to the planet. In particular, the same type of system (same stellar mass, same planet mass, same orbital period), as σ_ψ increases, would be detectable at increasingly smaller distances. In Figure 2 we show how the number of stars available to GAIA for astrometric planet searches would decrease as a function of the increasing final error accuracy, assuming that the number of objects scale with the cube of the radius (in pc) of a sphere centered around the Sun. If σ_ψ is increased by a factor 2 the number of stars available for investigation would already be reduced by an order of magnitude. In the limit for final astrometric accuracy equal to the one foreseen for DIVA and FAME on bright objects ($50 \mu\text{as}$),

only some 150 stars would probably fall within GAIA's horizon. The size of the sample would be so reduced that extra-solar planets would completely disappear from the GAIA science case.

3.2 Modeling the Observations

In order to quantify the scientific impact of GAIA global astrometry measurements in the field of extra-solar planets extensive simulations have been used during the last few years [13,16,20].

Future work will concentrate on: *a)* refinements of the models of observations and observables. In particular, the science object position as defined in the satellite's reference frame will be expressed as function of all possible kinematic and dynamical parameters and of all astrophysical effects which contribute to a significant motion of the stellar photocenter, at the level of the single-measurement error. To this aim, more realistic galaxy models will be used, together with detailed models of specific environments, which will be needed for example in the case of the search for planets in stellar associations; *b)* as new knowledge is obtained from continuous improvement in the understanding of the instrument errors and performance before launch, a more realistic error model for GAIA observations will be implemented, which includes all possible sources of instrumental and astrophysical systematic errors, and their correlations; *c)* for a proper assessment of the effectiveness of the overall search and optimization strategy, the analysis tools will have to be refined in order to obtain a realistic estimation process, which involves the implementation of refined models for global search and optimization strategies of starting guesses for the orbital parameters. To this end, actual ground-based (or simulated) spectroscopic data could be used jointly with the simulated astrometric dataset, to improve orbital solutions and determine the full three-dimensional motion of the analyzed systems.

References

- [1] R.P. Butler, G.W. Marcy, D.A. Fischer, et al., in *Planetary Systems in the Universe: Observation, Formation and Evolution*, IAU Symp. 202, ed. A. Penny, P. Artymowicz, A. M. Lagrange & S. Russell, in press (2000)
- [2] D. Naef, D.W. Latham, M. Mayor, et al., *A&A* **375**, L27 (2001)
- [3] R.P. Butler, G.W. Marcy, D.A. Fischer, et al., *ApJ* **526**, 916 (1999)
- [4] M. Mayor, D. Naef, F. Pepe, et al., in *Planetary Systems in the Universe: Observation, Formation and Evolution*, IAU Symp. 202, ed. A. Penny, P. Artymowicz, A. M. Lagrange & S. Russell, in press (2000)
- [5] G.W. Marcy, R.P. Butler, S.S. Vogt, et al., *ApJ*, submitted (2001)
- [6] D.A. Fischer, G.W. Marcy, R.P. Butler, et al., *ApJ*, to be published (2002)
- [7] S. Udry, M. Mayor, D. Queloz, in *Planetary Systems in the Universe: Observation, Formation and Evolution*, IAU Symp. 202, eds. A. Penny, P. Artymowicz, A. M. Lagrange and S. Russell, in press (2000)
- [8] G.W. Marcy, R.P. Butler, D.A. Fischer, et al., *ApJ*, submitted (2001)
- [9] S.G. Els, M.F. Sterzik, F. Marchis, et al., *A&A*, submitted, 2001
- [10] G.W. Henry, G.W. Marcy, R.P. Butler, et al., *ApJ* **529**, L41 (2000)
- [11] T.F. Stepinski, D.C. Black, *A&A*, **371**, 250 (2001)
- [12] M. Mayor, S. Udry, J.L. Halbwachs, et al., in *Birth and Evolution of Binary Stars*, IAU Symp. 200, ASP Conf. Proc., ed. B. Reipurth & H. Zinnecker, in press (2001)
- [13] M.G. Lattanzi, A. Spagna, A. Sozzetti, et al., *MNRAS* **317**, 211 (2000)
- [14] O. Bienaymé, A.C. Robin, M. Crézé, *A&A* **180**, 94 (1987)
- [15] G.W. Marcy, W.D. Cochran, M. Mayor, in *Protostars and Planets IV*, ed V. Mannings, A. P. Boss & S. Russell (Tucson: University of Arizona Press), p. 1285 (1999)
- [16] M.G. Lattanzi, A. Sozzetti, A. Spagna, in *From Extra-solar Planets to Cosmology: The VLT Opening Symposium*, eds. J. Bergeron & A. Renzini (Berlin: Springer-Verlag), p. 479 (1999)
- [17] J.F. Kasting, D.P. Whitmire, R.T. Reynolds, *Icarus* **101**, 108 (1993)
- [18] G.W. Wetherill, *Icarus* **119**, 219 (1996)
- [19] M.A.C. Perryman, K.S. de Boer, G. Gilmore, et al., *A&A* **369**, 339 (2001)
- [20] A. Sozzetti, S. Casertano, M.G. Lattanzi, et al., *A&A* **373**, L24 (2001)